THE CARBON DIOXIDE OF THE SOIL AIR

A THESIS

PRESENTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF CORNELL UNIVERSITY FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

BY

HAROLD WORTHINGTON TURPIN

SEPTEMBER, 1918

Reprinted from Memoir 32, April, 1920, of Cornell University Agricultural Experiment Station.

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H. W. Turpin

Carbonic acid has long been recognized as an important soil solvent. On this point, at least, authorities are well agreed, but from the data available it is not yet clear what factors are most important in controlling the production of carbon dioxide in the soil. It is generally conceded, however, that a large proportion of the carbon dioxide found is due to soil microorganisms. The significance of plant roots in this connection has been recognized by some investigators, while others appear to be not quite decided as to how important plant-root excretions are.

HISTORICAL REVIEW

IMPORTANCE OF THE CARBON DIOXIDE IN THE SOIL

That carbon dioxide in solution is an important soil solvent has been shown by Stoklasa and Ernest (1909).[1] These workers point out that when ground gneiss and basalt are mixed with nutrient solutions, the amount of phosphorus and potassium absorbed by the plants grown is directly proportional to the carbon dioxide produced per gram of dry matter of the roots.

Aberson (1910) concluded, as a result of studies with young plants, that, while the excretions from plant roots may not be sufficiently concentrated (in carbon dioxide) to have a marked effect in dissolving insoluble materials, still the mucilaginous covering of the root hairs, containing a saturated solution of carbon dioxide, is entirely sufficient to bring into solution the insoluble soil constituents with which it comes in contact, especially the phosphates.

The limited usefulness, as a solvent, of the carbon dioxide secreted by plant roots is pointed out by Pfeiffer and Blanck (1912), who show that in soils treated with phosphates the carbon dioxide given off by plant roots is not a sufficient solvent to account for all the mineral nutrients obtained by the plant from the soil.

[1] Data in parenthesis refer to *Bibliography*, page 349.

Besides its importance as a direct solvent in the soil, carbon dioxide has considerable significance as an indicator of certain soil activities. Hutchinson (1912) observed a relationship between the biological activities and the amount of carbon dioxide in the soil. Russell (1915, a and b) noticed a close parallelism between the carbon-dioxide and the nitrate production in the soil, there being more of these constituents in spring and fall than in midsummer and winter. It was pointed out later by Russell and Appleyard (1915) that the curves for the bacterial numbers, the nitrate production, and the carbon-dioxide content in the soil thruout the season, show marked similarity, indicating that the carbon dioxide may serve to some extent as an indicator of other soil activities. Neller (1918), however, could find in his experiments no correlation between the ammonia production and the carbon dioxide formed, except in cases in which he used pure cultures of bacteria. The lack of correlation he attributed to the predominating influence of fungi in the soil.

In addition to its importance as a direct solvent in the soil and as an indicator of certain soil activities, carbonic acid may possibly be significant as an inhibitor of the activity of soil organisms and perhaps even of plant growth. Large quantities of carbon dioxide in the air have been found by numerous investigators to be detrimental to the growth of the higher plants. E. Wollny (1897) observed an increased production of carbon dioxide with an increase in the organic matter in the soil, but the increase to the unit of organic matter was less with the larger application. This Wollny attributed to the inhibiting effect of carbon dioxide on the bacterial activities. The work of Plummer (1916), however, showed that exceedingly large amounts of carbon dioxide do not interfere with the activities of the ammonifying and nitrifying organisms, provided, in the latter case, that the oxygen supply is not reduced below a certain minimum. The same investigator showed that the maximum carbon-dioxide production in the soil corresponds with the point of maximum nitrification. In studies on the carbon dioxide produced in lysimeter tanks, Bizzell and Lyon (1918) noted a marked decrease in the production of this gas after the blooming period of an oat crop on Dunkirk clay loam. This decrease, they say, "was apparently due to the depressing effect of the crop on production by bacterial action." Such a decrease was not found to take place on a Volusia silt loam.

FACTORS AFFECTING THE AMOUNT OF CARBON DIOXIDE IN THE SOIL AIR

Soil organisms

Most investigators consider that soil organisms play a large part in the production of carbon dioxide in the soil. Pettenkofer (1858, 1871, 1873, 1875) concluded, as a result of his investigations, that most of the carbon dioxide in the soil is due to living organisms.

Later, E. Wollny (1880b) found that there is only a small production of carbon dioxide in an atmosphere of hydrogen gas, while chloroform almost completely stops the power of the soil to form carbon dioxide. He concluded that carbon dioxide is produced largely by bacteria.

Further confirmation of this is to be found in the studies of Dehérain and Demoussy (1896), which showed that sterile soil at a temperature of 22° C. produces only insignificant amounts of carbon dioxide. Stoklasa and Ernest (1905), after working with beets, clover, oats, and other plants, noted that a bare soil produced, in one hundred and fifty days, more than twice the carbon dioxide produced by a crop of wheat on the same area in sixty days. They observed also a correlation between the numbers of bacteria and the carbon dioxide produced at different depths in the soil. Hutchinson (1912) concluded that carbon-dioxide production is a reliable measure of bacterial activity.

Soil conditions

Where soil conditions are favorable to the action of bacteria, the carbon-dioxide content is usually high. For example, Stoklasa (1911) obtained the greatest production of this gas in a soil that was well aerated, slightly alkaline, and well supplied with readily available plant nutrients. This was found by E. Wollny (1897), Russell and Appleyard (1915), and others, to be especially true in the case of soils having readily available organic matter. Very small amounts of carbon dioxide were found in the swamp rice lands of India by Harrison and Aiyer (1913), showing that unfavorable soil conditions are associated with a low content of carbon dioxide.

Seasonal conditions

Russell and Appleyard (1915, 1917) emphasized the importance of seasonal conditions on the carbon-dioxide content of the soil. In their investigations they observed that a rise of temperature is accompanied

by an increase in carbon dioxide. The same fact had been previously noted by Möller (quoted by E. Wollny, 1880 a), by Dehérain and Demoussy (1896), by Stoklasa and Ernest (1905), and by Leather (1915), and was later mentioned by Potter and Snyder (1916).

Carbon-dioxide production was found by the Rothamsted investigators (Russell and Appleyard, 1917) to be correlated with moisture and rainfall. Previously E. Wollny (1880 a) had observed that increasing amounts of water up to 9 per cent, in a quartz sand mixed with peat, resulted in an increase in the carbon dioxide. Dehérain and Demoussy (1896) found that there was an optimum water content for carbon-dioxide production in a garden soil. Van Suchtelen (1910) found the greatest amount of carbon dioxide when the soil with which he worked was 75 per cent saturated with water.

The relationship observed by Russell and Appleyard (1917) between the rainfall of the preceding week and the carbon-dioxide content of the soil, was believed by them to be due largely to the oxygen dissolved in the rain water. That this may be true is shown by the earlier work of E. Wollny (1897), and also by that of Fodor (1875), who showed that there is a relationship between the carbon-dioxide content and the oxygen of the soil, indicating that the carbon dioxide is probably produced by oxidation processes.

The crop

The evidence available thus seems to point to bacteria as the chief source of soil carbon-dioxide. There are some data, however, which show that plants may play a considerable part in the production of this gas in the soil.

Stoklasa and Ernest (1909) and Aberson (1910) noted that the roots of plants excrete large amounts of carbon dioxide. That the gas so formed is not insignificant is proved by the fact that field studies conducted at Rothamsted by Russell and Appleyard (1917) showed a considerably higher content of carbon dioxide in cropped soil than appeared in the bare soil, this being especially marked in May, at the time of the most active growth of the plant, and at the time of ripening. The same condition was observed by Bizzell and Lyon (1918) in the case of an oat crop on Dunkirk clay loam, where the greatest production of carbon dioxide took place at about the time of blooming. Potter and Snyder (1916) observed

similar results with timothy, but they were unable to decide whether or not this increase of carbon dioxide was due to the plant-root excretions or to the decay of root particles that had died during the growth of the crop. The work of Stoklasa and Ernest (1905) showed that the younger the plant is, the greater is the amount of carbon dioxide formed. Kossowitch (1904) noted that mustard grown in quartz sand and nutrient solutions produced an increased amount of carbon dioxide up to the time of blooming. This was observed also by Barakov (1910) in the case of plants growing in lysimeters.

That different kinds of plants produce different amounts of carbon dioxide has been shown by Lau (1906), who found that potatoes and legumes give off more carbon dioxide than do other crops. Red clover, beets (*Beta vulgaris*), and oats were found by Stoklasa and Ernest (1905) to produce more carbon dioxide than other plants, and in the order named. Russell and Appleyard (1915), however, could find no difference in the carbon-dioxide content of soils on which different species of plants were growing.

Chemical factors

From the brief survey given, it would seem correct to say that most of the carbon dioxide found in the soil is the result of biological activity. There is some evidence, however, showing that chemical action may play a small part. E. Wollny (1880 b) noted a very slight production of carbon dioxide in soil treated with chloroform. The same investigator demonstrated later (E. Wollny, 1897) that organic matter in the absence of oxygen reduces manganese and iron oxides and forms carbon dioxide. Very little carbon-dioxide production in sterilized soil kept at a temperature of 22° C. was observed by Dehérain and Demoussy (1896). They found, however, a very considerable production of carbon dioxide in soil heated to 90° C. and above. An oxidizing enzyme in the excretions of the root hairs was considered by Molisch (1888) to be capable of producing carbon dioxide from organic substances. It is probable that carbon dioxide produced by chemical means forms an extremely small part of the total carbon dioxide found in the soil.

Summary

In this review of the literature of the subject, certain facts stand out. Authorities are agreed that bacteria play an important part, probably

the most important part of all the factors concerned, in the production of carbon dioxide in the soil. Climatic factors, such as temperature, rainfall, and air supply, have a marked effect on the carbon-dioxide content of the soil. Crops increase the amount of carbon dioxide in the soil, either by direct excretions from the roots or thru the decay of root particles from the growing crop. Finally, the nature of the soil itself causes marked differences in the production of carbon dioxide.

The results reported in this paper confirm some of the above conclusions, but they also show that the influence of the crop has been underemphasized.

EXPERIMENTAL WORK

In the author's first experiment, a study was made for two seasons (1917 and 1918) in the greenhouse, with soil cropped to oats and with uncropped soil. The object was to try to establish some definite relationship between the carbon dioxide in a cropped soil and that in an uncropped soil, where the crop itself introduced the only variable. Such a relationship having been established, it was decided to determine in the second experiment whether or not it would hold for a different crop. The third experiment was designed to analyze the factors concerned in the production of carbon dioxide, and, if possible, to assign to each its respective part.

EXPERIMENT 1

The cylinders illustrated in figure 44 were used in the first experiment. These cylinders, eight in number, were made of galvanized iron, coated inside with a layer of paint to insure their being air-tight at the joints and to prevent rusting. They were 3 feet high by 1 foot in diameter, and each had a cone-shaped bottom leading to the cocks on the outside as indicated in figure 45.

The cone-shaped bottom was filled with gravel, above which was placed a 12-inch layer of soil from the second foot of the field soil. Above this was placed a foot of surface soil. The soil used was Dunkirk clay loam. The moisture in the soil was maintained thruout the course of the experiment at 30 per cent on the oven-dry basis. The soil was covered with a half-inch layer of quartz sand in order to reduce the evaporation, the sand being added to the cropped soil immediately after seeding. The dry weight of the soil in each of the cans was 94.3 pounds.

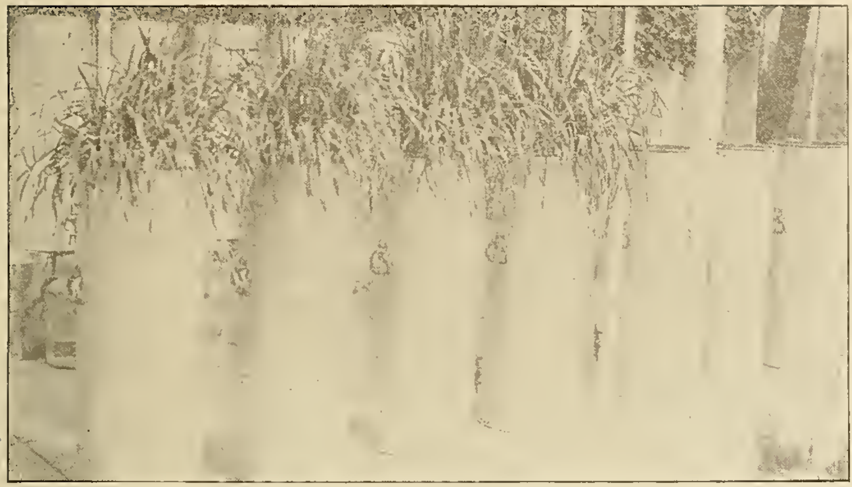

Fig. 44. cans used in first experiment

The four cans at the left contain an oat crop, which is shown at the period of its growth a month before the maximum amount of carbon dioxide was found in the air of the cropped soil

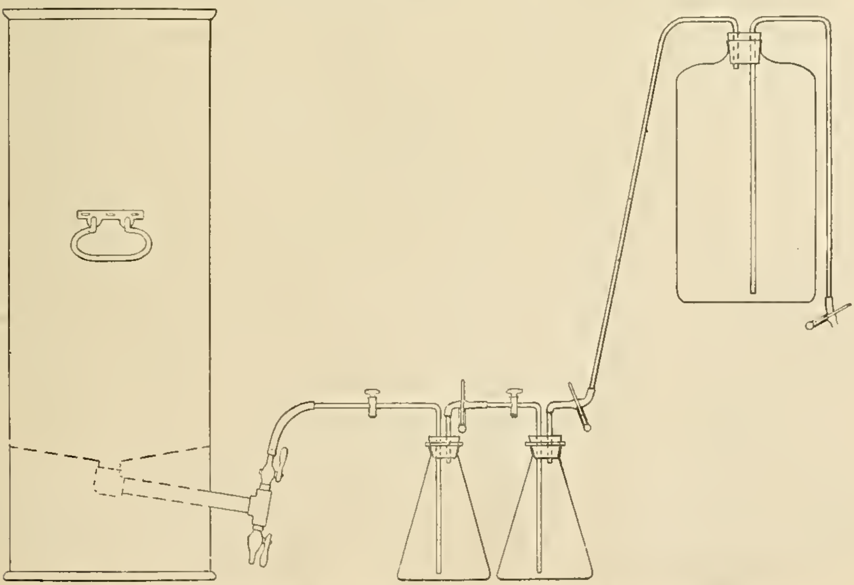

Fig. 45. arrangement of cylinder, sampling flasks, and aspirator

Before seeding, some preliminary studies were made in order to ascertain the best method of obtaining the sample of soil air for analysis. It seemed impracticable to use any method other than one that could be carried out rapidly, since it was planned to run the test for two seasons and to take the samples twice each week thruout the year. As a result of the preliminary studies, it was found that by aspirating four liters of air thru the soil cans in five minutes, and passing the air thru two graduated 500-cubic-centimeter Erlenmeyer flasks, samples could be obtained in the two flasks which checked with each other, indicating that the air originally present in the flasks had been replaced by a representative sample of the air in the soil. If more or less than four liters was aspirated thru the soil, the amounts of carbon dioxide in the two flasks did not check, indicating, in the first case, that the original air in the soil had been replaced by air from the atmosphere and that some of the latter was passing into the flasks, and in the second case that the original air in the flasks had not been completely replaced in the flask nearer the aspirator. The method of sampling is shown in figure 45. After the aspiration was completed, the cocks on the flasks were closed and the flasks were removed to the headhouse, where they were allowed to reach room temperature. The excess pressure in the flasks was relieved by opening one of the cocks for a moment. The temperature was noted at this point, as all calculations were reduced to per cent by volume of carbon dioxide at standard atmospheric conditions, that is, 760 millimeters pressure and 0° C.

Excess of standard barium hydroxide was next run into the flasks. The volume of the barium hydroxide added was noted, and was subtracted from the total volume of the flask. The cocks were then closed, and the flasks were allowed to stand, with occasional vigorous shaking, for about thirty minutes, after which the excess barium hydroxide was determined by titrating with standard oxalic acid whose equivalent in terms of carbon dioxide had been previously determined by titrating with standard potassium permanganate solution.

The method of aspirating air thru the soil has been criticized by Potter and Snyder (1916) in a paper describing experiments in which they determined the carbon dioxide evolved by drawing a current of air continuously over the soil surface. They maintain that the occasional drawing of air thru the soil will result in a temporary decrease in the content of carbon dioxide, which, however, will soon be restored by the

activities of the soil, and this accumulation of carbon dioxide will, by the mass action law, finally result in a retardation of further production of the gas. On the other hand, they maintain that by drawing a current of air continuously over the surface of the soil, conditions more nearly similar to those obtaining in the field will result. This may be true for experiments conducted in a quiet room; but in the greenhouse, where there is a circulation of air, there is ample opportunity for diffusion to take place from the soil, especially where, as in these experiments, one of the lower cocks of the soil can was always left open, so that a sample taken at any particular time should be truly representative of the carbon dioxide actually present under normal conditions.

It has been pointed out by Leather (1915) that usually only about 25 per cent of the carbon dioxide in the soil is in the gaseous state, the remainder being dissolved in water. It is reasonable to suppose that, once the soil water is saturated with this gas, any further production of carbon dioxide will tend to increase the content in the soil air. Considering these facts, then, it will be seen that the method used in these tests will not give, and was not intended to give, absolute amounts of carbon dioxide; but it nevertheless should yield reliable relative values.

On April 2, 1917, the soil, which is a heavy clay loam rich in silt and having a lime requirement of about 3000 pounds to the acre (Veitch), was brought up to 30 per cent moisture content on the oven-dry basis. Four of the cans were seeded to White Russian oats. A half-inch layer of quartz sand was then spread over the surface of the soil in the eight cans.

From April 12 to September 28 the samples were taken twice a week. From September 29 the sampling was done approximately once in two weeks until February 7, 1918, after which date the samples were again taken twice a week. The second crop of oats was planted on January 9. Some fifty seeds were usually sown, and the plants were thinned out in the course of two weeks to fifteen in each can. In the season of 1917, one plant became infected with smut, and on June 13 this plant was removed, together with one plant from each of the other cans. To maintain the moisture content of the cropped cans at 30 per cent (oven-dry basis) frequent waterings were necessary, especially at the time of most vigorous growth. At that period the cropped cans were irrigated once a day. The amount of water added was recorded in order to see whether or not there was any relationship between the transpiration and the carbon-

dioxide production in the cropped soil. Since only about a quarter of a pound of water was lost in a week from the uncropped soil, tap water was used in all cases, as the small loss by evaporation could not possibly introduce a disturbing element in the form of an accumulation of soluble salts in the soil.

Results

On each date of sampling, the samples were taken in duplicate from each of the eight cans. Thus eight samples were obtained from the cropped soil and eight from the bare soil. Since all of the four cropped cans were treated in identically the same manner, the data for the duplicate samples from the cropped cans were averaged. This was done also in the case of the bare soil.

It seemed fair to average the data obtained from the cans in each set because in all cases the differences were small. This is shown by the very small probable error. The data for the oat crops of 1917 and 1918 are given in tables 1 and 2 (appendix, pages 353 to 356), each figure for carbon dioxide in these two tables being the average of eight determinations. These summarized results are represented diagrammatically in figures 46 and 47.

Effect of crop

The content of carbon dioxide at the beginning of the experiment was 0.28 per cent by volume for both cropped and uncropped soil. From that time on, as may be seen from figures 46 and 47, the amount of carbon dioxide in the uncropped soil in no case reached that in the cropped soil — not even after the removal of the crop. The latter point may perhaps be explained by the fact that since the roots of the crop were not removed from the soil at harvesting, they somewhat increased the available supply of organic matter. The results reported here are directly opposite to those of Bizzell and Lyon (1918), who worked with the same Dunkirk clay loam under field conditions and found that subsequent to the removal of the oat crop a marked decrease in carbon dioxide below that in the uncropped soil took place. This was not found to be the case, however, with the Volusia silt loam used by these investigators.

A study of figure 46 shows that in the season of 1917 there was a marked increase in the carbon dioxide in the cropped soil from the beginning of May, a month after seeding, until the maximum, 2 per cent, was reached

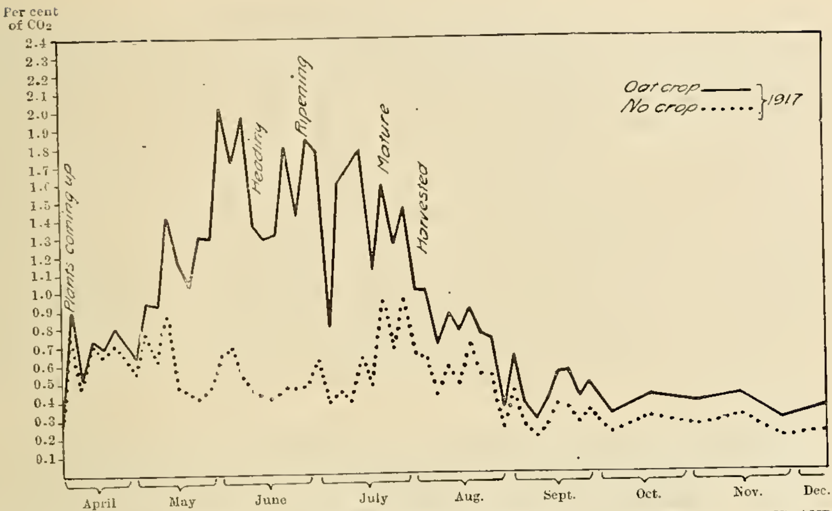

FIG. 46. CARBON DIOXIDE IN AIR FROM DUNKIRK CLAY LOAM CROPPED TO OATS AND FROM THE SAME SOIL LEFT BARE, 1917

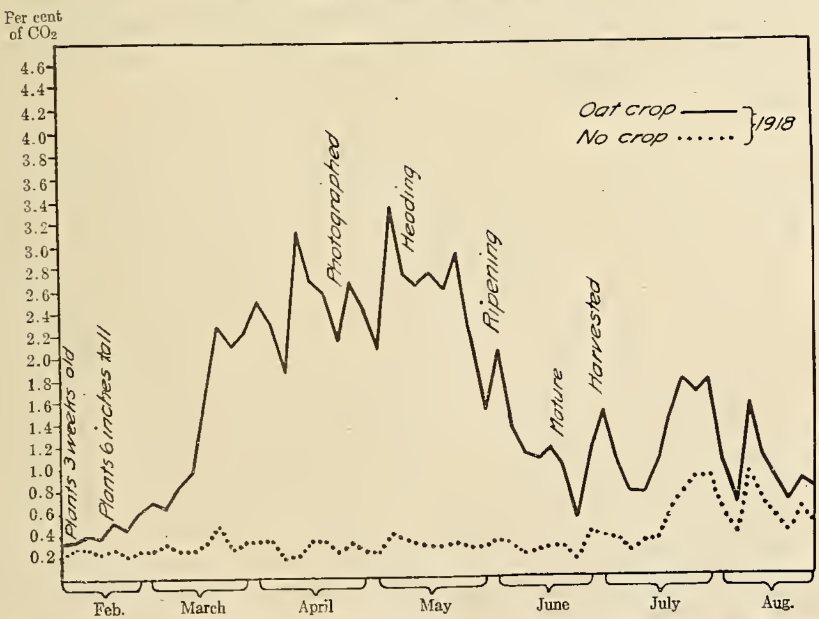

FIG. 47. CARBON DIOXIDE IN AIR FROM DUNKIRK CLAY LOAM CROPPED TO OATS AND FROM THE SAME SOIL LEFT BARE, 1918

in the first week of June, at the time when the plants were starting to head. Thereafter the general tendency of the curve for the cropped soil was toward a decrease, altho it was not until the middle of July, two weeks previous to harvesting, that this decrease was very marked. It was pointed out by Russell and Appleyard (1917) that in their experiments a large increase in carbon dioxide was observed in the cropped soil at the time of ripening; but, as can be seen from figures 46 and 47, in neither 1917 nor 1918 was any such increase noted in this work. If anything, the ripening was accompanied by a marked decrease in carbon dioxide, as is shown especially for the season of 1918 (fig. 47). Subsequent to the removal of the crop, the carbon dioxide in the cropped soil continued to decrease, but never to a point below or equal to that in the uncropped soil.

It is interesting to note that in 1917, fluctuations in the content of carbon dioxide in the uncropped soil were accompanied by similar variations in the cropped soil during the early part of the season and subsequent to harvesting. This was not true during the period of active growth of the plant, which would seem to indicate that at that time the life activity of the crop itself, rather than that of the soil organisms, is playing the dominant part in controlling the production of carbon dioxide.

What has been said for the season of 1917 holds for 1918 also. During the latter season, however, there was a much more marked increase in the carbon dioxide of the cropped soil. By the 11th of April, three months after seeding, more than 3 per cent of carbon dioxide was found, as compared with a little less than 0.2 per cent in the uncropped soil. This occurred four weeks previous to heading. Thereafter the content of carbon dioxide in the cropped soil increased to the maximum of 3.34 per cent, which occurred a week before heading and coincident with the time of rapid elongation of the culms. Following the maximum there was a steady decline. The decrease was especially marked during early June, when the upper glumes were beginning to turn yellow and the plants were starting to mature. In figure 44 (page 325) the plants are shown a month before the period of maximum carbon-dioxide production.

Since the maximum of 3.34 per cent of carbon dioxide found in the soil was about the same as that noted by Bizzell and Lyon (1918) in their studies with Dunkirk clay loam cropped to oats, it is evident that the decrease in the production of carbon dioxide in the cropped soil below

that in the uncropped soil after the removal of the crop, reported by these investigators, may not be due to interference with bacterial activities, since in the work reported in the present paper no such action on the soil organisms, as evidenced by a decrease in carbon-dioxide production, was observed. It may be possible that the decrease noted by Bizzell and Lyon was due to some other effect of the crop, such as, for example, the reduction of the soil moisture. It has been pointed out in the review of the literature of the subject that some investigators have noted a decrease in carbon dioxide where the moisture was reduced below a certain optimum amount. On referring to figure 46 it will be seen that early in July, 1917, the carbon dioxide in the cropped soil showed a marked decrease. This was due to the drying-out of the soil when, thru an oversight, it was not watered for two days.

It has been pointed out that the carbon dioxide in the cropped soil was somewhat higher (about 30 per cent) in 1918 than it was in 1917. The results for the two seasons are not strictly comparable, because in 1917 the crop was sown in April whereas in 1918 the seeding was made in January. Also, in 1917 the number of plants was reduced to fourteen in each pot, while in 1918 there were fifteen. However, the total dry weight of the mature crop from the four cans in 1917 was 494.5 grams, as against 416 grams in 1918.

Carbon-dioxide and water relationships

As has already been stated, a record was kept of the amount of water added to the cropped cans in order to maintain them at a moisture content of 30 per cent (oven-dry basis). The sand mulch on the soil, as has been pointed out also, was so effective that the loss in moisture on the cropped cans could be regarded as due entirely to transpiration.

The total amount of water lost on the cropped cans each week was determined in 1917 and 1918 for a period of ten weeks during which the crop was making the most active growth. These amounts, together with the average weekly content of carbon dioxide in the cropped and the uncropped soil, are indicated in tables 3 and 4 (appendix, pages 357 to 358), columns A, C, and E. The difference between the carbon dioxide in the cropped and that in the uncropped soil is given in column F of the same tables. The carbon dioxide produced to each pound of water used is shown in columns G and H. The figures in column G were obtained

by dividing the weekly carbon-dioxide percentage in the cropped soil after the carbon dioxide in the bare soil had been subtracted, by the weekly loss of water in pounds. The figures in column H, however, were obtained by dividing the weekly carbon-dioxide percentage in the cropped soil by the weekly loss of water without first subtracting the carbon dioxide in the bare soil from that in the cropped soil.

The relationship between the carbon dioxide produced in the cropped soil (from which has been subtracted the carbon dioxide in the bare soil), and the water transpired by the crop, is shown graphically in figures 48 and 49. There seems to be a relationship between the amount of water transpired and the carbon dioxide produced by plants, as is indicated

Fig. 48. Relation between water transpired and carbon dioxide produced by an oat crop for the ten weeks during which its growth was most vigorous, 1917

by tables 3 and 4 and by figures 48 and 49. The illustrations show that the curves for the water transpired each week, and for the carbon dioxide obtained by subtracting the carbon dioxide in the bare soil from that in the cropped soil, follow each other closely. The data given in the

tables and plotted in the curves are for the period of ten weeks during which the plants were growing most actively. Before and after this period no relationship was found to exist between the amount of water transpired and the carbon dioxide produced by the plants.

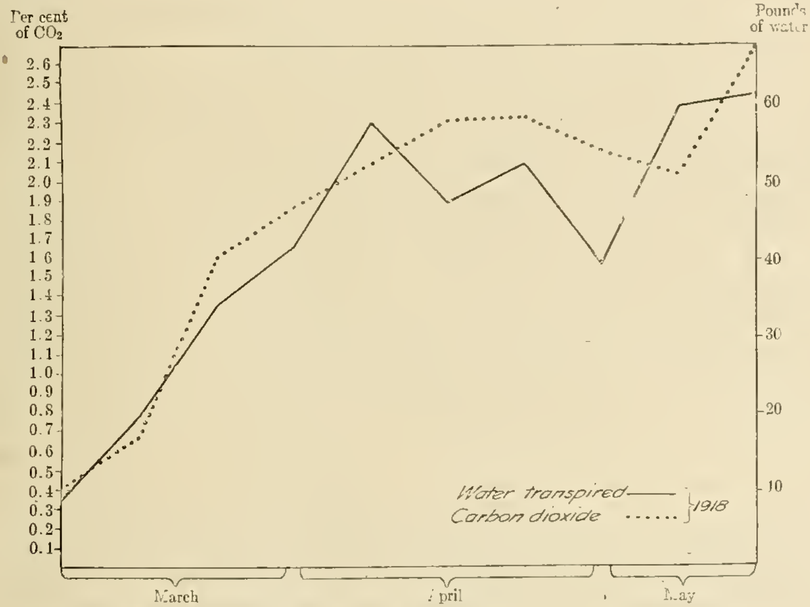

FIG. 49. RELATION BETWEEN WATER TRANSPIRED AND CARBON DIOXIDE PRODUCED BY AN OAT CROP FOR THE TEN WEEKS DURING WHICH ITS GROWTH WAS MOST VIGOROUS, 1918

It is seen in columns G and H of tables 3 and 4 that the percentage of carbon dioxide produced to each pound of water transpired, approaches a constant much more nearly when the carbon dioxide in the uncropped soil is subtracted from that in the cropped soil. The smaller coefficients of variability of 22.5 ± 3.74 as compared with 37.4 ± 5.65 in 1917, and 15.1 ± 2.32 as against 19.17 ± 3.12 in 1918, bring out this fact fairly clearly. If it is assumed that the amount of carbon dioxide produced and the amount of water transpired are indications of life activity, then the relationships found between the carbon dioxide in the soil, and the water transpired, would hold only when the carbon dioxide is produced

by the crop alone. When the carbon dioxide in the uncropped soil was subtracted from the carbon dioxide found in the cropped soil, and this figure was divided by the amount of water transpired, there resulted approximately a constant of 0.024 $\pm$ .0012 (column G) with a coefficient of variability of 22.5 $\pm$ 3.74 for 1917, and a constant of 0.043 $\pm$ .0014 with a coefficient of variability of 15.1 $\pm$ 2.32 for 1918. When the carbon dioxide in the uncropped soil, which may be attributed to bacterial activity, was not subtracted (column H), there resulted a constant of 0.042 $\pm$ .0031 with a coefficient of variability of 37.4 $\pm$ 5.65 for 1917, and a constant of 0.053 $\pm$ .0022 with a coefficient of variability of 19.17 $\pm$ 3.12 for 1918.

This shows that the constants in the latter cases are not nearly so dependable as those in the former, indicating that the carbon dioxide produced by the crop is probably the difference between the carbon dioxide in the cropped soil and that in the bare soil. That the values obtained are not perfect constants can hardly be wondered at when it is recalled that the carbon dioxide as determined was not absolute, but relative.

In this connection it may be pointed out that there seems to be some ground for concluding that there is a relationship between the water transpired by the plant and the carbon-dioxide content of the soil.

While it is not disputed that the mechanism by which the water is actually lost from the leaves of the plant is purely physical and not at all associated with vital plant activity, yet the process by which the water is brought into the leaves and into a condition to be transpired may well be considered as being associated with the life activities of the plant. Many investigators have maintained that there is a distinct relationship between the life activities of plants and the water transpired. For example, as early as 1849 Lawes (1850) considered that the comparative rate of transpiration of water to some extent indicated the relative activity of the processes of the plant. He drew these conclusions from studies with wheat, barley, beans, peas, and clover, in which he compared the amount of ash and dry matter obtained from the plants with the water given off by them. He found that the larger the amount of dry matter, the greater was the quantity of water transpired. These views are supported by the investigations of Sorauer (1878, 1880), but the work of Walter Wollny (1898) leads to an opposite conclusion. In 1905 Livingston (1905) worked with wheat seedlings and concluded that total transpiration is as good a criterion for comparing the relative growth of plants in

different media as is the weight of the plant itself. Hasselbring (1914), however, after growing plants under cheesecloth and in the open, stated that the mere passage of water thru the plant had no influence on the assimilatory activity of the plant, provided the water supply did not fall below a certain minimum required to maintain turgor of the cells. Stoklasa and Ernest (1909) determined the carbon dioxide given off by different plants grown in various nutrient solutions, and obtained the results presented in table 5 (appendix, page 358). These figures show that there is a definite relationship between the total dry weight of different crops and the carbon dioxide produced. The average of 0.037 milligram of carbon dioxide to each milligram of dry matter seems to be independent of the kind of plant used in the test.

From the short review given, it would seem that the evidence is in favor of the assumption that transpiration is related to life activity of plants as indicated by a relationship between the dry matter and the water transpired. The work of Stoklasa and Ernest (1909) would point to a correlation between the carbon dioxide produced and the dry matter in the plant.

Effect of temperature and atmospheric pressure

The relationship between the temperature and the atmospheric pressure at the time of sampling, and the carbon dioxide in the air of the uncropped soil, is shown graphically in figures 50 and 51 for the seasons of 1917 and 1918, respectively. The temperature at each time of sampling was found to be approximately representative of the temperature for the preceding twelve-hours period. The pressure also would probably represent the average of several hours preceding the sampling.

On the whole the figures bring out only a few striking facts. High temperatures were usually accompanied by a high percentage of carbon dioxide, while high atmospheric pressures were usually associated with a low carbon-dioxide content. High pressures along with high temperatures gave fairly high contents of carbon dioxide, indicating that temperature has a more marked effect than pressure. When the temperature and the pressure were medium there appeared to be no relationship with the carbon-dioxide content. Very low temperatures were always accompanied by a low content of carbon dioxide; but, while a very low pressure did not necessarily mean a high carbon-dioxide content, it was usually associated with such a condition.

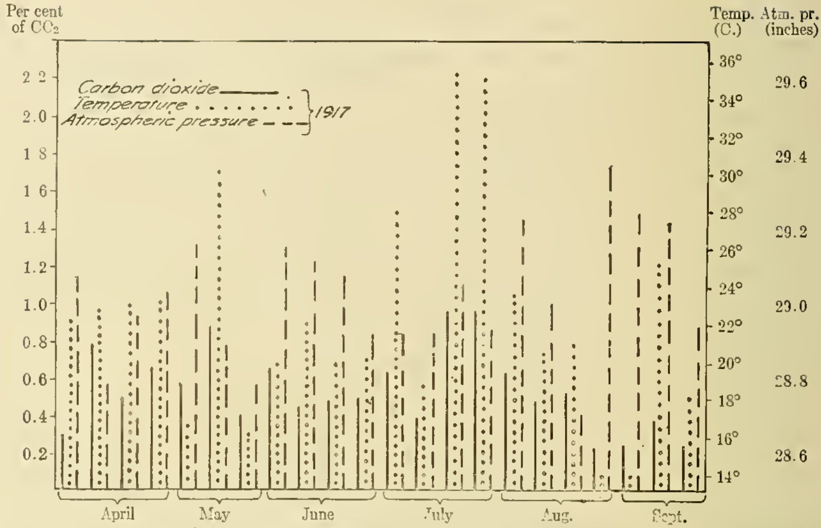

FIG. 50. RELATION BETWEEN THE TEMPERATURE OF THE SOIL AT THE TIME OF SAMPLING, THE ATMOSPHERIC PRESSURE, AND THE CARBON DIOXIDE IN THE AIR OF THE UNCROPPED SOIL, 1917

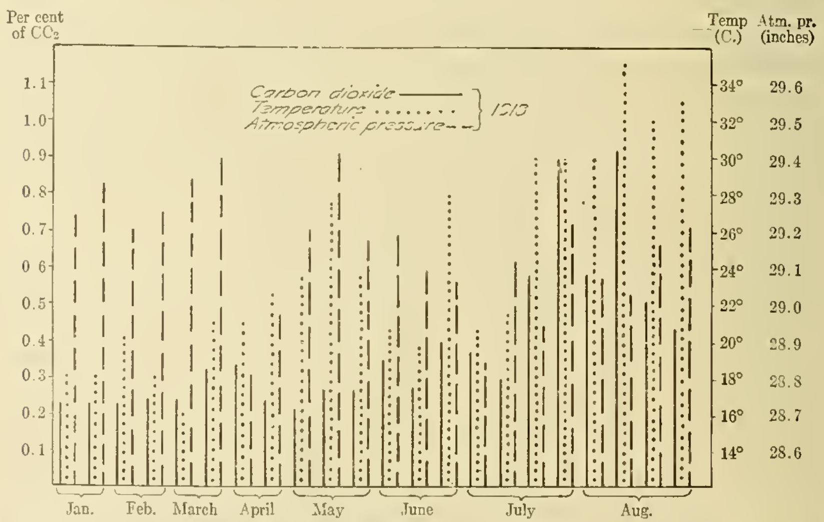

FIG. 51. RELATION BETWEEN THE TEMPERATURE OF THE SOIL AT THE TIME OF SAMPLING, THE ATMOSPHERIC PRESSURE, AND THE CARBON DIOXIDE IN THE AIR OF THE UNCROPPED SOIL, 1918

Summary of experiment 1

The results of the first experiment may be summarized as follows:

1. Soils cropped to oats always contained a greater amount of carbon dioxide than did the corresponding bare soils.

2. The crop had a residual effect, increasing the carbon-dioxide content above that in the uncropped soil.

3. The difference between the amount of carbon dioxide in the cropped soil and that in the uncropped soil at the period of most active crop growth, divided by the amount of water transpired by the crop, gave an apparent constant which varied with the season.

4. The fact just stated may indicate that the difference between the amount of carbon dioxide produced in the cropped soil and that in the uncropped soil represented the amount produced by the crop.

5. It is thus evident that the carbon dioxide from plants and from soil organisms accumulated independently.

6. Fluctuations in the amount of carbon dioxide in the uncropped soil were due largely to temperature and pressure variations. High pressures produced low contents of carbon dioxide, while high temperatures caused high production of carbon dioxide, and vice versa.

EXPERIMENT 2

The object of the second experiment was to determine the influence of some crop other than oats on the production of carbon dioxide. The crop used in this case was common millet (*Setaria italica*).

Immediately after the harvesting of the 1918 oat crop, millet was planted on the same soil and in the same cylinders as were used in experiment 1. For experiment 2 the surface layer of sand was entirely removed from the soil, which was then thoroly stirred to a depth of about three inches. The millet was seeded on four of the soils, of which two had previously been in oats and two had been bare. The object in using these two different sets was to try to produce some differences in the two crops of millet. It was thought that possibly the millet growing on the soil which had been previously cropped twice to oats, might not grow well, and in such a case a comparison could be made between a good and a poor crop of millet.

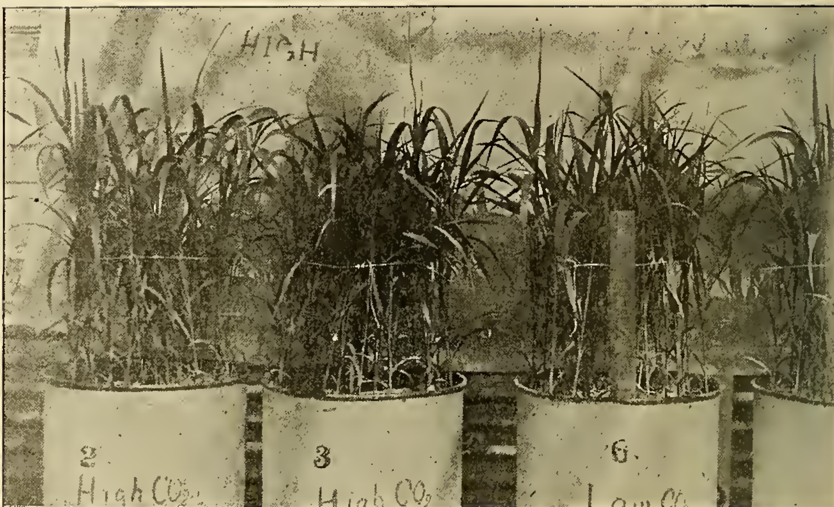

FIG. 52. MILLET CROPS SIX WEEKS AFTER SEEDING, ON THE TWO SOILS HAVING HIGH AND LOW INITIAL CONTENTS OF CARBON DIOXIDE, RESPECTIVELY

Close view, showing details

The crop was planted on July 1. Within three weeks after planting, the crop on each can had been thinned out until forty plants remained. The number of plants to a pot was reduced in the next week to thirty. At first the samples were taken twice a week, as in the case of experiment 1; but later — from the middle of August — when the crop was making very rapid growth, samples were taken every day. Toward the end of August the samples were taken every other day. As in experiment 1, the moisture in the soil was maintained at 30 per cent (oven-dry basis).

At the time when the experiment was discontinued, the plants were completely headed. In the case of series 1 (soil previously cropped to oats) the plants were beginning to show signs of maturing; in series 2 (soil previously bare), however, the grain was still between the milk stage and the dough stage.

The crops on series 1 and 2 were identical in all details until a few days after heading. This may be seen in figures 52 to 55. Thereafter the plants in series 2 maintained their dark green color, while those in

FIG. 53. MILLET CROPS SIX WEEKS AFTER SEEDING, ON THE TWO SOILS HAVING HIGH AND LOW INITIAL CONTENTS OF CARBON DIOXIDE, RESPECTIVELY

Same as figure 52, but showing cylinders

series 1 gradually became light green, until finally, when the experiment was stopped in September, the latter were beginning to mature while those in series 2 had not yet begun to show signs of ripening.

Results

The results of experiment 2 are summarized in table 6 (appendix, page 359), in which each figure represents the average of two duplicate samplings from each of two pots, an average of four samplings in all.

FIG. 54. MILLET CROPS SEVEN AND ONE-HALF WEEKS AFTER SEEDING, ON THE TWO SOILS HAVING HIGH AND LOW INITIAL CONTENTS OF CARBON DIOXIDE, RESPECTIVELY

Close view, showing details

These data are presented diagrammatically in figures 56, 57, and 58, the first two representing the data for series 1 and 2, respectively, and the third giving these two sets of curves on one sheet.

It will be noticed that the carbon dioxide in the cropped soils and that in the uncropped soils remained the same for the first four weeks after seeding. Thereafter the curves for the cropped soils separated fairly rapidly from those for the bare soils. In this respect there is no difference between the oats and the millet. It will be observed, however, that whereas the two oat crops attained their point of maximum carbon-dioxide production shortly before heading, the millet crops both gave the most carbon dioxide just ten days after heading. In order to bring out this point more clearly, curves showing the relationship between the amount of carbon dioxide in the oat soil (1917) and that in the millet soil (series 2) have been plotted together in figure 59, in such a manner that the carbon dioxide produced at the period of heading of each of the two crops is on the same ordinate, with the data for a few weeks

FIG. 55. MILLET CROPS SEVEN AND ONE-HALF WEEKS AFTER SEEDING, ON THE TWO SOILS HAVING HIGH AND LOW INITIAL CONTENTS OF CARBON DIOXIDE, RESPECTIVELY

Same as figure 54 but showing cylinders

before and a few weeks after the heading period plotted to the left and to the right of this point, respectively.

Since the experiment was discontinued before the millet crops matured, it is not possible to say whether or not the curve for the later period of

FIG. 56. CARBON DIOXIDE IN AIR FROM DUNKIRK CLAY LOAM PREVIOUSLY CROPPED TWICE TO OATS, CROPPED TO MILLET, AND FROM THE SAME SOIL LEFT BARE, 1918

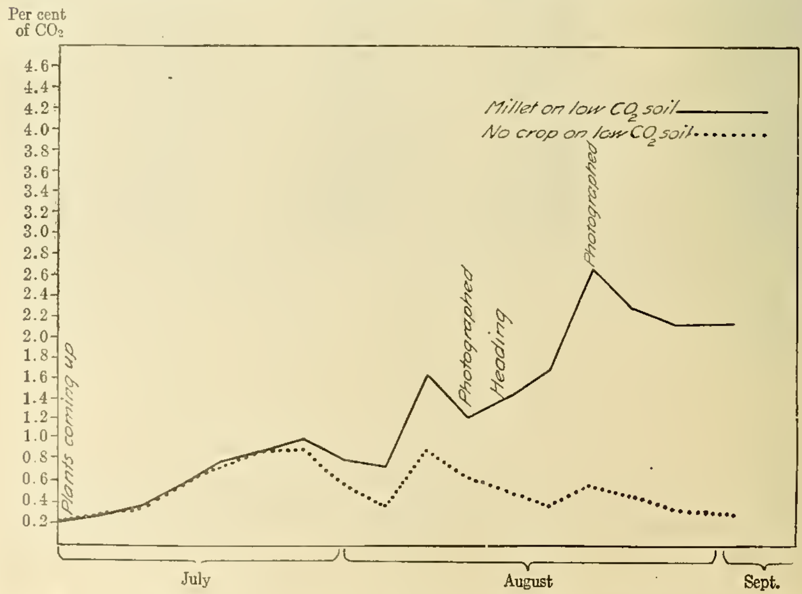

FIG. 57. CARBON DIOXIDE IN AIR FROM DUNKIRK CLAY LOAM NOT PREVIOUSLY CROPPED, CROPPED TO MILLET, AND FROM THE SAME SOIL LEFT BARE, 1918

FIG. 58. RELATION BETWEEN THE AMOUNTS OF CARBON DIOXIDE IN AIR FROM CROPPED AND FROM UNCROPPED DUNKIRK CLAY LOAM HAVING HIGH AND LOW INITIAL CONTENTS OF CARBON DIOXIDE, RESPECTIVELY

FIG. 59. RELATION BETWEEN THE AMOUNTS OF CARBON DIOXIDE IN AIR FROM DUNKIRK CLAY LOAM CROPPED TO OATS AND MILLET, RESPECTIVELY, BEFORE AND AFTER THE CROPS HEADED

growth of the millet would resemble in general that for the oat crops. The general tendency of the curve after August 25 was to fall as the plants advanced toward maturity, as in the case of the oat crops. It will be noticed from figure 59 that the actual amount of carbon dioxide produced on the soil cropped to millet was much the same as that produced on the oat soil. The maxima for the two oat crops of 1917 and 1918 were, respectively, 2.031 per cent and 3.343 per cent, while the corresponding figures for the millet crops in series 1 and 2 were 3.345 per cent and 2.715 per cent. It must be remembered, however, that there were but fifteen oat plants as compared with thirty millet plants; so that it may be concluded that an individual oat plant causes the production of about twice as much carbon dioxide as is produced by a millet plant.

Summary of experiment 2

From the results of the second experiment it may be concluded that a soil cropped to millet causes about the same fluctuations in carbon-dioxide production as are found in a soil growing an oat crop. In general, however, the oat crop gives the greatest production of carbon dioxide previous to heading, while the millet has its most marked effect a week or two after heading. It would seem also that an individual millet plant causes the production of approximately half as much carbon dioxide as an individual oat plant. From the close agreement between the two curves shown in figures 56, 57, and 58, for series 1 and 2, it may be assumed that in spite of slight differences in the previous treatment of the soil the excess carbon dioxide due to the crop was fairly similar where the crops growing showed no apparent differences in vigor. This is indicated also in figures 52 to 55, which show the two crops at an early and at a later stage of growth, the crop on the soil previously cropped twice to oats being designated as a high-carbon-dioxide crop and that on the soil that was previously bare being called a low-carbon-dioxide crop.

EXPERIMENT 3

As is pointed out in the review of literature, it is not clear whether or not the increased amount of carbon dioxide observed in a cropped soil is due to the excretion of carbon dioxide by plant roots (plant activity) or to the decay of root particles from the growing crop (bacterial activity). Data obtained in experiment 3 seem to throw a little light on this question. In this experiment, cans 1, 2, 3, and 4, which had previously grown two

crops of oats, had a considerably higher content of carbon dioxide, even after the removal of the crop and especially for about two months after harvest, than did cans 5, 6, 7, and 8, which remained uncropped for the two seasons.

After the oat crop from cans 1, 2, 3, and 4 was harvested, on July 1, 1918, cans 2 and 3, and the uncropped cans 6 and 8, were seeded to millet. Cans 1, 2, 3, and 4 are here designated as the high-carbon-dioxide series, while cans 5, 6, 7, and 8 are called the low-carbon-dioxide series. Thus, in the high-carbon-dioxide series, cans 1 and 4 were bare and cans 2 and 3 were cropped to millet; in the low-carbon-dioxide series, cans 5 and 7 were bare and cans 6 and 8 were cropped. All these cans were sampled in the usual way for carbon dioxide, and the data obtained are given in table 7 (appendix, page 360). The samples were taken twice a week at first, and later they were taken daily. The moisture in the soil was maintained at or near 30 per cent (oven-dry basis).

Within a month of seeding, the crop was thinned to thirty plants to a can; so that at the time when the effect of the plants on the carbon dioxide became noticeable (a month after seeding), the number of plants was the same for all cans.

Results

In table 7 it is shown that the differences between the percentages of carbon dioxide in the cropped soil and those in the uncropped soil in the high-carbon-dioxide series, were approximately the same as the corresponding differences in the low-carbon-dioxide series. In table 8 (appendix, page 361) it is seen that the majority of the differences in carbon-dioxide production by the crop in the two series (as determined by the difference between the amount of carbon dioxide produced by the cropped soil and that produced by the uncropped soil) was well within the limits of the experimental error. It seems, therefore, that the crops produced carbon dioxide quite independently, and that this production was not affected by the amount of carbon dioxide in the soil, at least not within the limits set by this experiment. How closely the difference between the curves for the cropped soils corresponded with those for the bare soils is shown in figure 58 (page 343).

The relationship between the temperature of the soil at the time of sampling, and the carbon dioxide in the bare soil and also that due to the crop on the low-carbon-dioxide series (determined by the difference as

explained above), is shown in table 9 (appendix, page 362) and in figure 60. It will be noticed that increases in temperature were more frequently accompanied by rises in carbon dioxide in the bare soil (indicating a relationship between bacterial activity and carbon-dioxide production), than by rises in the carbon dioxide produced by the crop. In the latter

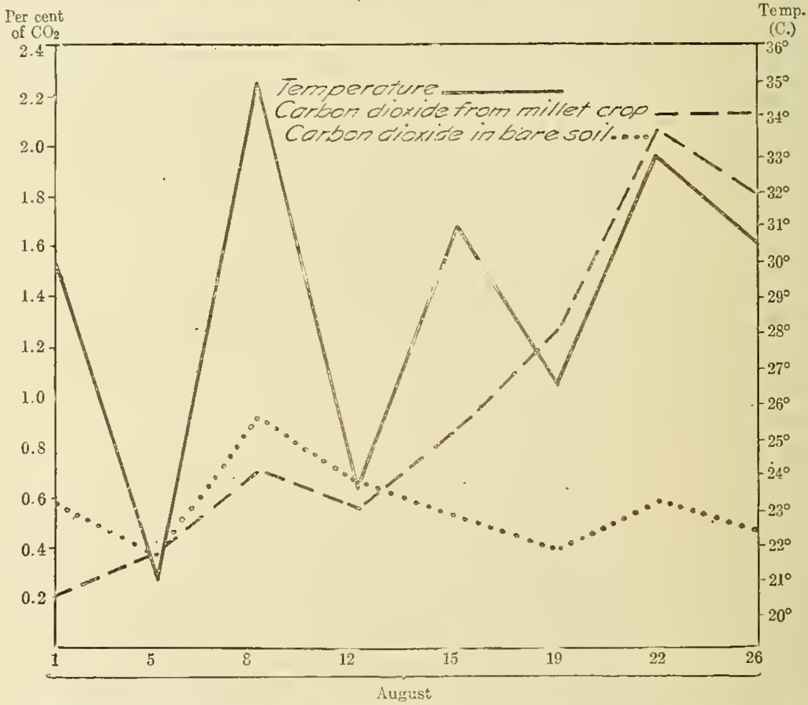

FIG. 60. RELATION BETWEEN THE CARBON DIOXIDE PRODUCED BY A MILLET CROP, THE CARBON DIOXIDE IN A BARE SOIL, AND THE TEMPERATURE OF THE SOIL AT THE TIME OF SAMPLING, 1918

case no such close relationship appeared, but the carbon dioxide increased gradually as the age of the plant advanced until the point of maximum carbon-dioxide production, after which there was a decline. This increase in carbon dioxide seems to have kept pace with the rate of growth of the plants. At the time when the plants ceased to grow actively (some time after heading), the carbon-dioxide production also fell off. If the excess

carbon dioxide in the cropped soil is due to the decomposition by bacteria of root particles thrown off from the growing crop, then one would expect to find that those factors which produce fluctuations in the carbon dioxide in the bare soil would produce corresponding, but more magnified, fluctuations in the cropped soil. But, as is pointed out above, a factor such as temperature did not produce corresponding changes in the two soils.

Again, if the decomposition of root particles from the growing crop gave rise to the increase of carbon dioxide in the cropped soil, it is reasonable to suppose that there would be a much larger increase in carbon dioxide at a time when the roots were beginning to die off rapidly, that is, toward the ripening period. Such, however, was not the case.

Summary of experiment 3

It is probable, therefore, that the larger part of the excess carbon dioxide produced in a cropped soil is due to respiratory activities of the plant roots, and that the amount resulting from the decay of root particles from the growing crop is small—altho after the crop has matured, any excess of carbon dioxide found is undoubtedly due to the decay of the mass of roots left in the soil. This excess, however, is very small when compared with the very large amounts of carbon dioxide found in the cropped soil at the time of heading, for example.

In support of the conclusion that the larger production of carbon dioxide in the cropped soil is due to respiratory activities of the plant roots, the data presented in experiment 1 show that there seems to be a correlation between the water requirements of the plant and the amount of carbon dioxide produced.

GENERAL SUMMARY

The results of the work reported in this paper with regard to the effect of crop and other factors on the production of carbon dioxide in a Dunkirk clay loam maintained at a constant moisture content of 30 per cent (oven-dry basis), may be summed up as follows:

1. An oat crop increased the production of carbon dioxide in the soil. This increase became marked after the first month from the time of seeding, and increased to a maximum just previous to or after the plants headed, after which there was a gradual decline.

2. Millet produced about the same increase in carbon dioxide as did oats, but the production of carbon dioxide by each millet plant was approximately half as much as the production by each oat plant. The most marked rise in the carbon-dioxide content of the soil occurred at a later period of growth in the case of the millet than in the case of the oats.

3. The cropped soil, after the crop was harvested, maintained a higher carbon-dioxide content than was found in the bare soil. This was due probably to the decomposition of plant roots left in the soil.

4. It would seem that increased plant activity (growth) is accompanied by increased carbon-dioxide production. This theory is supported by the fact that a relationship was shown between the carbon dioxide produced presumably by the crop, and the water transpired.

5. Fluctuations in the content of carbon dioxide in the bare soil were accompanied by similar fluctuations in the cropped soil only after the removal of the crop and before the crop had made much growth.

6. There appeared to be little relationship between the temperature of the soil at the time of sampling, and the carbon dioxide in the cropped soil or that assumed to be produced by the crop (determined by subtracting the carbon dioxide in the bare soil from that in the cropped soil).

7. In the bare soil the carbon dioxide was usually high during warm weather and low when the temperature decreased.

8. Very low atmospheric pressures were usually accompanied by an increase in the content of carbon dioxide in the bare soil.

9. The carbon dioxide produced presumably by the plant was about the same in soils having a high initial carbon-dioxide content as in those low in carbon dioxide, indicating the probability that plants and soil organisms act independently in producing carbon dioxide.

10. It is concluded from this work that the plant itself, and soil organisms, produce most of the carbon dioxide in the soil; that the plant often produces at the period of its most active growth many times as much carbon dioxide as is produced by soil organisms; and that the excess carbon dioxide in the soil growing a crop is due to respiratory activity of the plants rather than to the decay of root particles from the crop growing on the soil at the time of analysis.

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APPENDIX

TABLE 1. Carbon Dioxide (Per Cent by Volume) in Cropped and in Uncropped Soil (Oats, 1917)

Date of sampling	Temperature (centigrade)	Atmospheric pressure (inches)	Water added to maintain moisture content at 30 per cent (grams)	Carbon dioxide produced in		Difference (A—B)
				Cropped soil (A)	Uncropped soil (B)	
March 30	22.0°	29.06	....	0.285±:009	0.281±.006	0.004±.011
April 12	23.0°	28.78	....	0.909±.017	0.777±.014	0.132±.022
April 15	23.0°	28.98	1.75	0.526±.007	0.498±.009	0.028±.011
April 19	30.0°	29.22	2.75	0.741±.019	0.736±.003	0.005±.019
April 22	21.0°	29.12	3.00	0.698±.017	0.653±.004	0.045±.017
April 26	22.0°	29.06	4.50	0.813±.013	0.714±.008	0.099±.015
April 30	23.0°	29.02	3.75	0.737±.014	0.653±.007	0.084±.016
May 4	17.0°	29.15	2.50	0.640±.013	0.559±.007	0.081±.015
May 7	21.5°	29.16	5.75	0.943±.027	0.776±.009	0.167±.028
May 11	22.0°	28.82	7.25	0.931±.037	0.632±.006	0.299±.037
May 14	30.0°	28.88	11.00	1.422±.048	0.878±.015	0.544±.050
May 18	16.0°	29.00	16.75	1.166±.047	0.475±.003	0.691±.047
May 21	21.0°	29.05	14.00	1.034±.037	0.452±.003	0.582±.037
May 25	16.0°	28.78	11.25	1.307±.040	0.415±.004	0.892±.040
May 28	17.0°	28.77	14.50	1.297±.034	0.477±.002	0.820±.034
June 1	20.0°	29.07	20.25	2.031±.102	0.648±.007	1.383±.102
June 4	29.0°	29.27	15.75	1.708±.060	0.698±.011	1.010±.060
June 8	21.0°	28.88	23.75	1.982±.101	0.530±.002	1.452±.101
June 11	22.0°	29.10	20.75	1.365±.042	0.452±.005	0.913±.043
June 15	13.0°	29.07	27.00	1.292±.024	0.416±.002	0.876±.024
June 18	22.0°	29.17	20.50	1.315±.025	0.419±.007	0.896±.026
June 22	20.5°	29.15	31.25	1.809±.030	0.480±.009	1.329±.032
June 25	30.0°	29.55	27.00	1.412±.033	0.466±.007	0.946±.034
June 29	20.0°	28.91	39.50	1.846±.028	0.496±.003	1.350±.028
July 2	28.0°	28.92	24.00	1.778±.032	0.620±.008	1.158±.033
July 6	16.0°	29.16	....	0.799	0.393±.002	....
July 9	24.0°	28.95	25.00	1.614±.014	0.449±.008	1.165±.016
July 13	19.0°	28.92	20.00	1.699±.018	0.394±.001	1.305±.018
July 16	30.0°	29.14	16.00	1.781±.052	0.633±.007	1.148±.052
July 20	20.0°	29.24	7.50	1.111±.016	0.491±.005	0.620±.017
July 23	35.0°	29.05	8.00	1.595±.030	0.954±.015	0.641±.033
July 27	23.0°	28.99	6.00	1.261±.044	0.686±.007	0.575±.044
July 30	35.0°	28.93	3.50	1.475±.029	0.959±.007	0.516±.030
August 3	21.0°	29.07	6.00	1.040±.032	0.643±.007	0.397±.032
August 6	25.0°	29.22	3.50	1.028±.028	0.629±.007	0.399±.029
August 10	19.5°	29.05	1.50	0.706±.012	0.425±.003	0.281±.012
August 13	26.0°	29.21	2.75	0.876±.012	0.581±.005	0.295±.013
August 17	20.5°	29.00	1.25	0.781±.019	0.478±.003	0.303±.019
August 20	32.0°	28.97	....	0.909±.012	0.704±.002	0.205±.012
August 24	22.0°	28.71	....	0.765±.013	0.526±.007	0.239±.015

TABLE 1 (*concluded*)

Date of sampling	Temperature (centigrade)	Atmospheric pressure (inches)	Water added to maintain moisture content at 30 per cent (grams)	Carbon dioxide produced in		Difference (A−B)
				Cropped soil (A)	Uncropped soil (B)	
August 27	29.5°	29.20	....	0.729±.009	0.538±.005	0.191±.010
August 31	14.0°	29.37	....	0.345±.007	0.244±.001	0.101±.008
Sept. 3	25.0°	29.21	....	0.659±.015	0.488±.001	0.171±.015
Sept. 7	14.0°	29.23	....	0.376±.007	0.256±.003	0.120±.008
Sept. 10	14.5°	29.34	....	0.289±.004	0.195±.003	0.094±.005
Sept. 14	15.5°	29.41	....	0.385±.010	0.255±.007	0.130±.013
Sept. 17	25.0°	29.31	....	0.544±.008	0.378±.004	0.166±.009
Sept. 21	18.0°	29.06	....	0.554±.010	0.348±.005	0.206±.011
Sept. 24	24.0°	29.40	....	0.415±.003	0.266±.003	0.149±.004
Sept. 28	18.0°	28.93	....	0.495±.012	0.328±.003	0.167±.013
Oct. 5	16.0°	28.89	....	0.309±.010	0.211±.004	0.098±.011
Oct. 19	24.0°	28.92	....	0.404±.010	0.288±.006	0.116±.011
Nov. 2	17.0°	29.40	....	0.382±.008	0.259±.004	0.123±.009
Nov. 16	19.0°	29.08	....	0.424±.013	0.301±.016	0.123±.021
Nov. 30	17.0°	29.15	....	0.280±.008	0.192±.005	0.088±.010
Dec. 14	17.5°	28.69	....	0.356±.020	0.216±.007	0.140±.021

TABLE 2. CARBON DIOXIDE (PER CENT BY VOLUME) IN CROPPED AND IN UNCROPPED SOIL (OATS, 1918)

Date of sampling	Temperature (centigrade)	Atmospheric pressure (inches)	Water added to maintain moisture content at 30 per cent (grams)	Carbon dioxide produced in		Difference (A—B)
				Cropped soil (A)	Uncropped soil (B)	
Jan. 3	18.0°	29.24	....	0.373±.020	0.229±.005	0.144±.021
Jan. 16	18.5°	28.84	....	0.346±.014	0.162±.002	0.184±.014
Jan. 31	18.0°	29.32	....	0.315±.009	0.223±.006	0.092±.011
Feb. 7	20.0°	29.20	....	0.318±.010	0.226±.002	0.092±.010
Feb. 11	20.0°	28.98	....	0.340±.010	0.249±.009	0.091±.013
Feb. 14	22.5°	28.97	....	0.401±.010	0.255±.009	0.146±.013
Feb. 18	18.0°	29.68	....	0.370±.010	0.221±.006	0.149±.012
Feb. 21	20.0°	28.75	5.00	0.509±.014	0.258±.008	0.251±.016
Feb. 25	20.5°	28.83	3.75	0.445±.009	0.195±.006	0.250±.011
Feb. 28	20.0°	29.25	5.00	0.595±.010	0.240±.008	0.355±.012
March 4	16.0°	29.34	5.75	0.695±.016	0.236±.008	0.459±.018
March 7	20.0°	28.96	3.25	0.639±.017	0.295±.007	0.344±.018
March 11	16.0°	29.54	9.75	0.834±.010	0.236±.006	0.598±.020
March 14	20.0°	28.48	9.75	0.969±.029	0.226±.006	0.743±.029
March 18	18.0°	29.15	14.25	1.688±.027	0.285±.006	1.403±.028
March 21	25.0°	28.88	19.75	2.290±.060	0.471±.012	1.819±.062
March 25	18.0°	28.84	24.00	2.103±.030	0.259±.009	1.844±.031
March 28	21.0°	29.39	17.50	2.224±.055	0.319±.010	1.905±.056
April 1	21.0°	28.81	30.75	2.514±.039	0.331±.010	2.183±.041
April 4	20.0°	29.08	27.00	2.314±.033	0.318±.006	1.996±.034
April 8	19.0°	29.39	33.25	1.865±.025	0.170±.009	1.695±.026
April 11	20.5°	29.26	14.00	3.129±.033	0.188±.004	2.941±.034
April 15	20.5°	29.22	22.25	2.704±.072	0.320±.006	2.384±.072
April 18	24.0°	28.83	29.75	2.580±.085	0.311±.004	2.269±.085
April 22	21.0°	28.68	24.25	2.129±.089	0.211±.005	1.918±.089
April 25	23.5°	29.28	15.00	2.678±.056	0.303±.006	2.375±.057
April 29	22.5°	28.97	38.50	2.418±.040	0.236±.005	2.182±.041
May 2	23.5°	29.20	21.00	2.069±.046	0.211±.003	1.858±.046
May 6	23.0°	29.07	31.00	3.343±.029	0.389±.003	2.954±.029
May 9	27.0°	28.93	30.25	2.741±.041	0.345±.004	2.396±.041
May 13	23.0°	28.92	24.25	2.643±.045	0.296±.004	2.347±.045
May 16	27.5°	29.41	21.00	2.753±.071	0.266±.004	2.487±.071
May 20	22.0°	29.12	23.00	2.600±.081	0.276±.004	2.324±.081
May 23	24.0°	29.30	17.75	2.934±.044	0.295±.006	2.639±.044
May 27	21.5°	29.05	17.25	2.153±.065	0.259±.006	1.894±.065
May 30	23.5°	29.17	16.75	1.518±.018	0.264±.005	1.254±.018
June 3	20.5°	29.19	27.00	2.045±.011	0.344±.005	1.701±.012
June 6	22.5°	29.10	18.25	1.361±.015	0.299±.005	1.062±.015
June 10	17.5°	29.11	17.75	1.120±.017	0.199±.003	0.921±.017
June 13	21.5°	28.77	10.75	1.070±.017	0.220±.004	0.850±.018
June 17	19.5°	29.09	15.50	1.170±.007	0.271±.005	0.899±.009
June 20	24.0°	29.21	11.75	1.004±.009	0.249±.002	0.755±.009
June 24	14.0°	29.00	5.50	0.519±.007	0.140±.002	0.379±.007

TABLE 2 (*concluded*)

Date of sampling	Temperature (centigrade)	Atmospheric pressure (inches)	Water added to maintain moisture content at 30 per cent (grams)	Carbon dioxide produced in		Difference (A−B)
				Cropped soil (A)	Uncropped soil (B)	
June 27	28.0°	29.06	6.00	1.169±.019	0.396±.003	0.773±.019
July 1	20.5°	28.84	5.25	1.500±.041	0.369±.006	1.131±.041
July 4	28.5°	29.33	....	1.026±.014	0.336±.005	0.690±.015
July 8	17.0°	28.99	....	0.763±.040	0.215±.002	0.548±.040
July 11	21.5°	29.12	....	0.745±.024	0.295±.007	0.450±.025
July 15	19.0°	29.12	....	1.028±.018	0.333±.004	0.695±.019
July 18	30.0°	28.94	....	1.430±.040	0.578±.011	0.852±.042
July 22	23.0°	29.31	....	1.778±.004	0.750±.021	1.028±.021
July 25	30.0°	29.22	....	1.648±.035	0.895±.017	0.753±.039
July 29	24.0°	29.14	....	1.788±.001	0.920±.021	0.868±.021
August 1	30.0°	29.07	....	1.020±.038	0.580±.029	0.440±.048
August 5	21.0°	28.92	....	0.653±.006	0.375±.017	0.278±.018
August 8	35.0°	29.03	....	1.563±.013	0.920±.036	0.643±.038
August 12	23.5°	29.16	....	1.088±.028	0.665±.012	0.423±.030
August 14	28.0°	29.07	....	1.315±.007	0.790±.026	0.525±.027
August 15	31.0°	29.21	....	0.885±.024	0.525±.021	0.360±.032
August 16	32.0°	29.16	....	0.835±.016	0.505±.021	0.330±.026
August 17	29.5°	29.50	....	0.760±.021	0.478±.023	0.282±.031
August 19	26.5°	29.53	....	0.668±.006	0.400±.014	0.268±.015
August 21	33.0°	29.21	....	0.715±.026	0.430±.010	0.285±.028
August 22	33.0°	29.17	....	0.888±.013	0.588±.018	0.300±.022
August 23	33.0°	29.10	....	0.988±.004	0.633±.014	0.355±.015
August 24	34.0°	29.02	....	1.145±.005	0.695±.007	0.450±.009
August 26	30.5°	28.96	....	0.788±.016	0.468±.006	0.320±.018
August 27	30.0°	29.28	....	0.688±.006	0.448±.020	0.240±.021

TABLE 3. RELATION BETWEEN THE CARBON DIOXIDE IN THE CROPPED SOIL DURING THE PERIOD OF MOST ACTIVE PLANT GROWTH, AND THE WATER TRANSPIRED EACH WEEK (OATS, 1917)

Date	Water transpired (grams)	Total water transpired each week (grams) (A)	Cropped soil: Carbon dioxide (per cent) (B)	Cropped soil: Average carbon dioxide for the week (per cent) (C)	Uncropped soil: Carbon dioxide (per cent) (D)	Uncropped soil: Average carbon dioxide for the week (per cent) (E)	Difference in carbon dioxide C−E (F)	Per cent of carbon dioxide to each pound of water: F/A (G)	Per cent of carbon dioxide to each pound of water: C/A (H)
May 7....	5.75	13.00	0.943	0.937	0.776	0.704	0.233	0.018	0.072
May 11...	7.25		0.931		0.632				
May 14...	11.00	27.75	1.422	1.294	0.878	0.677	0.617	0.022	0.047
May 18...	16.75		1.166		0.475				
May 21...	14.00	25.25	1.034	1.174	0.452	0.434	0.740	0.029	0.046
May 25...	11.25		1.314		0.415				
May 28...	14.50	34.75	1.297	1.664	0.477	0.563	1.101	0.032	0.048
June 1....	20.25		2.031		0.648				
June 4....	15.75	39.50	1.708	1.845	0.698	0.614	1.231	0.031	0.047
June 8....	23.75		1.982		0.530				
June 11...	20.75	47.75	1.365	1.329	0.452	0.434	0.895	0.019	0.028
June 15...	27.00		1.292		0.416				
June 18...	20.50	51.75	1.315	1.562	0.419	0.450	1.112	0.021	0.030
June 22...	31.25		1.809		0.480				
June 25...	27.00	66.50	1.412	1.629	0.466	0.481	1.148	0.017	0.024
June 29...	39.50		1.846		0.496				
July 2....	24.00	......	1.778	......	0.620	0.507	....	....	....
July 6....	.....		.....		0.393				
July 9....	25.00	45.00	1.614	1.657	0.449	0.422	1.235	0.027	0.037
July 13...	20.00		1.699		0.394				
Mean........................								0.024 ±.0012	0.042 ±.0031
Standard deviation................								0.0054 ±.0009	0.0136 ±.0022
Coefficient of variability...........								22.5 ±3.74	37.40 ±5.65

TABLE 4. RELATION BETWEEN THE CARBON DIOXIDE IN THE CROPPED SOIL DURING THE PERIOD OF MOST ACTIVE PLANT GROWTH, AND THE WATER TRANSPIRED EACH WEEK (OATS, 1918)

Date	Water transpired (grams)	Total water transpired each week (grams) (A)	Cropped soil: Carbon dioxide (per cent) (B)	Cropped soil: Average carbon dioxide for the week (per cent) (C)	Uncropped soil: Carbon dioxide (per cent) (D)	Uncropped soil: Average carbon dioxide for the week (per cent) (E)	Difference in carbon dioxide C−E (F)	Per cent of carbon dioxide to each pound of water: F/A (G)	Per cent of carbon dioxide to each pound of water: C/A (H)
March 4	5.75	9.00	0.695	0.667	0.236	0.266	0.401	0.045	0.074
March 7	3.25		0.639		0.295				
March 11	9.75	19.50	0.834	0.902	0.236	0.231	0.671	0.034	0.046
March 14	9.75		0.969		0.226				
March 18	14.25	34.00	1.688	1.989	0.285	0.378	1.611	0.047	0.059
March 21	19.75		2.290		0.471				
March 25	24.00	41.50	2.103	2.164	0.259	0.289	1.875	0.045	0.052
March 28	17.50		2.224		0.319				
April 1	30.75	57.75	2.514	2.414	0.331	0.325	2.089	0.036	0.042
April 4	27.00		2.314		0.318				
April 8	33.25	47.25	1.865	2.497	0.170	0.179	2.318	0.049	0.053
April 11	14.00		3.129		0.188				
April 15	22.25	52.00	2.704	2.642	0.320	0.316	2.326	0.045	0.051
April 18	29.75		2.580		0.311				
April 22	24.25	39.25	2.129	2.404	0.211	0.257	2.147	0.055	0.061
April 25	15.00		2.678		0.303				
April 29	38.50	59.50	2.418	2.244	0.236	0.224	2.020	0.034	0.038
May 2	21.00		2.069		0.211				
May 6	31.00	61.25	3.343	3.042	0.389	0.367	2.675	0.044	0.050
May 9	30.25		2.741		0.345				
Mean								0.043 ±.0014	0.053 ±.0022
Standard deviation								0.0065 ±.0010	0.0102 ±.0015
Coefficient of variability								15.1 ±2.32	19.17 ±3.12

TABLE 5. RELATION BETWEEN THE DRY WEIGHT OF THE CROP AND THE CARBON DIOXIDE GIVEN OFF BY PLANT ROOTS

(From Stoklasa and Ernest, 1909)

Crop	Total dry matter produced in 84 days (milligrams)	Total carbon dioxide produced in 84 days (milligrams)	Milligrams of carbon dioxide produced to each milligram of dry matter
Barley	34,493	1,267	0.037
Rye	27,046	1,053	0.039
Oats	26,215	793	0.030
Wheat	18,375	784	0.043
Average	26,532	974	0.037

TABLE 6. CARBON DIOXIDE (PER CENT BY VOLUME) IN CROPPED AND IN UNCROPPED SOIL (MILLET, 1918)

Date of sampling	Carbon dioxide produced in			
	Series 1 (high CO_2 soil)		Series 2 (low CO_2 soil)	
	Cropped (per cent)	Bare (per cent)	Cropped (per cent)	Bare (per cent)
July 8	0.713±.016	0.763±.040	0.210±.002	0.215±.002
July 11	0.763±.006	0.745±.024	0.283±.001	0.295±.007
July 15	1.045±.031	1.028±.018	0.358±.001	0.333±.004
July 18	1.455±.050	1.430±.040	0.578±.001	0.578±.001
July 22	1.803±.032	1.778±.004	0.795±.014	0.750±.021
July 25	2.015±.079	1.648±.035	0.908±.059	0.895±.017
July 29	1.923±.101	1.788±.001	1.008±.054	0.920±.021
August 1	1.305±.055	1.020±.038	0.798±.039	0.580±.029
August 5	1.133±.006	0.653±.006	0.750±.052	0.375±.017
August 8	2.115±.017	1.563±.013	1.628±.161	0.920±.036
August 12	2.025±.021	1.088±.028	1.223±.018	0.665±.012
August 14	2.448±.028	1.315±.007	1.710±.043	0.790±.026
August 15	1.864±.016	0.885±.024	1.405±.012	0.525±.021
August 16	1.950±.010	0.835±.016	1.480±.033	0.505±.021
August 17	2.108±.018	0.760±.021	1.683±.049	0.478±.023
August 19	2.040±.048	0.668±.006	1.683±.042	0.400±.014
August 21	2.288±.016	0.715±.026	1.948±.016	0.430±.010
August 22	3.098±.023	0.888±.013	2.655±.055	0.588±.018
August 23	3.095±.060	0.988±.004	2.715±.074	0.633±.014
August 24	3.345±.035	1.145±.005	2.690±.060	0.695±.007
August 26	2.465±.005	0.788±.016	2.275±.064	0.468±.006
August 27	2.198±.009	0.688±.006	2.133±.075	0.448±.020
August 28	2.245±.031	0.690±.036	1.958±.056	0.348±.004
August 29	2.093±.039	0.613±.004	2.120±.088	0.358±.006
August 31	1.983±.011	0.590±.007	2.245±.114	0.370±.010
September 3	1.770±.021	0.533±.011	2.143±.068	0.310±.005

TABLE 7. CARBON DIOXIDE (PER CENT BY VOLUME) IN CROPPED AND IN UNCROPPED SOILS HAVING DIFFERENT INITIAL CARBON-DIOXIDE CONTENTS (MILLET, 1918)

Date of sampling	Carbon dioxide produced in				Difference in carbon dioxide produced by various soils				
	High CO_2 soil		Low CO_2 soil						
	Cropped (A)	Bare (B)	Cropped (C)	Bare (D)	I (A—C)	II (B—D)	III (A—B)	IV (C—D)	V (III—IV)
July 8	0.713±.016	0.763±.040	0.210±.092	0.215±.002	+0.503±.016	+0.548±.040	—0.050±.043	—0.005±.003	—0.045±.043
July 11	0.763±.006	0.745±.024	0.283±.001	0.295±.007	+0.480±.006	+0.450±.025	+0.018±.025	—0.012±.007	+0.030±.026
July 15	1.045±.031	1.028±.018	0.358±.001	0.333±.001	+0.687±.031	+0.695±.019	+0.017±.036	+0.025±.004	—0.008±.036
July 18	1.455±.050	1.430±.040	0.578±.001	0.578±.001	+0.877±.051	+0.852±.042	+0.025±.064	0.000±.016	+0.025±.066
July 22	1.803±.032	1.778±.004	0.795±.014	0.750±.021	+1.008±.035	+1.028±.021	+0.025±.032	+0.045±.025	—0.020±.041
July 25	2.015±.079	1.648±.035	0.908±.059	0.895±.017	+1.107±.099	+0.753±.039	+0.367±.086	+0.013±.061	+0.354±.106
July 29	1.923±.101	1.788±.001	1.008±.054	0.920±.021	+0.915±.114	+0.868±.021	+0.135±.101	+0.088±.058	+0.047±.116
August 1	1.305±.055	1.020±.038	0.798±.039	0.580±.029	+0.507±.067	+0.440±.048	+0.285±.067	+0.218±.049	+0.067±.082
August 5	1.133±.006	0.653±.006	0.750±.052	0.375±.017	+0.383±.052	+0.278±.018	+0.480±.008	+0.375±.055	+0.105±.055
August 8	2.115±.017	1.563±.013	1.628±.161	0.920±.036	+0.487±.162	+0.643±.038	+0.552±.021	+0.708±.170	—0.156±.167
August 12	2.025±.021	1.088±.028	1.223±.018	0.665±.012	+0.802±.028	+0.423±.030	+0.937±.035	+0.558±.022	+0.379±.041
August 14	2.448±.028	1.315±.007	1.710±.043	0.790±.026	+0.738±.051	+0.525±.027	+1.133±.029	+0.920±.050	+0.213±.058
August 15	1.864±.016	0.885±.024	1.405±.012	0.525±.021	+0.459±.035	+0.360±.032	+0.979±.041	+0.880±.024	+0.103±.048
August 16	1.950±.010	0.835±.016	1.480±.033	0.505±.021	+0.470±.034	+0.330±.026	+1.115±.019	+0.975±.039	+0.140±.047
August 17	2.108±.018	0.760±.021	1.683±.049	0.478±.023	+0.425±.052	+0.282±.031	+1.348±.028	+1.205±.054	+0.143±.061
August 19	2.040±.048	0.668±.006	1.683±.042	0.400±.014	+0.357±.065	+0.268±.015	+1.372±.048	+1.283±.044	+0.089±.066
August 21	2.288±.016	0.715±.026	1.948±.016	0.430±.010	+0.340±.023	+0.285±.028	+1.573±.031	+1.518±.019	+0.055±.036
August 22	3.098±.023	0.888±.013	2.655±.055	0.588±.018	+0.443±.060	+0.300±.022	+2.210±.026	+2.067±.058	+0.143±.064
August 23	3.095±.060	0.988±.004	2.715±.074	0.633±.014	+0.380±.095	+0.355±.015	+2.107±.062	+2.082±.075	+0.025±.096
August 24	3.345±.035	1.145±.005	2.690±.060	0.695±.007	+0.655±.062	+0.450±.009	+2.200±.018	+1.995±.060	+0.205±.063
August 26	2.465±.005	0.788±.016	2.275±.064	0.468±.006	+0.190±.064	+0.320±.018	+1.677±.018	+1.807±.064	—0.130±.067
August 27	2.198±.009	0.688±.006	2.133±.075	0.448±.020	+0.065±.075	+0.240±.021	+1.510±.011	+1.685±.077	—0.175±.078
August 28	2.245±.031	0.690±.036	1.958±.056	0.348±.004	+0.287±.061	+0.342±.036	+1.555±.048	+1.619±.056	—0.055±.074

TABLE 8. CARBON DIOXIDE (PER CENT BY VOLUME) PRODUCED APPARENTLY BY THE MILLET CROP, 1918. DETERMINED BY SUBTRACTING THE AMOUNT OF CARBON DIOXIDE IN THE BARE SOIL FROM THAT IN THE CROPPED SOIL

Date of sampling	Carbon dioxide apparently produced by millet crop in		Difference (I—II)
	High CO_2 soil (I)	Low CO_2 soil (II)	
July 8	—0.050±.043	—0.005±.003	—0.045±.043
July 11	+0.018±.025	—0.012±.007	+0.030±.026
July 15	+0.017±.036	+0.025±.004	—0.008±.036
July 18	+0.025±.064	0.000±.016	+0.025±.066
July 22	+0.025±.032	+0.045±.025	—0.020±.041
July 25	+0.367±.086	+0.013±.061	+0.354±.106
July 29	+0.135±.101	+0.088±.058	+0.047±.116
August 1	+0.285±.067	+0.218±.049	+0.067±.082
August 5	+0.480±.008	+0.375±.055	+0.105±.055
August 8	+0.552±.021	+0.708±.170	—0.156±.167
August 12	+0.937±.035	+0.558±.022	+0.379±.041
August 14	+1.133±.029	+0.920±.050	+0.213±.058
August 15	+0.979±.041	+0.880±.024	+0.103±.048
August 16	+1.115±.019	+0.975±.039	+0.140±.047
August 17	+1.348±.028	+1.205±.054	+0.143±.061
August 19	+1.372±.048	+1.283±.044	+0.089±.066
August 21	+1.573±.031	+1.518±.019	+0.055±.036
August 22	+2.210±.026	+2.067±.058	+0.143±.064
August 23	+2.107±.062	+2.082±.075	+0.025±.096
August 24	+2.200±.018	+1.995±.060	+0.205±.063
August 26	+1.677±.018	+1.807±.064	—0.130±.067
August 27	+1.510±.011	+1.685±.077	—0.175±.078
August 28	+1.555±.048	+1.610±.056	—0.055±.074

TABLE 9. Carbon Dioxide (Per Cent by Volume) in Cropped and in Uncropped Soil of Low Initial Carbon-Dioxide Content (Millet, 1918)

Date of sampling	Temperature (centigrade)	Atmospheric pressure (inches)	Carbon dioxide produced in		Difference (I—II)
			Cropped soil (I)	Uncropped soil (II)	
July 8.....	17.0°	28.99	0.210±.002	0.215±.002	—0.005±.003
July 11....	21.5°	29.12	0.283±.001	0.295±.007	—0.012±.007
July 15....	19.0°	29.12	0.358±.001	0.333±.004	+0.025±.004
July 18....	30.0°	28.94	0.578±.001	0.578±.001	0.000±.016
July 22....	23.0°	29.31	0.795±.014	0.750±.021	+0.045±.025
July 25....	30.0°	29.22	0.908±.059	0.895±.017	+0.013±.061
July 29....	24.0°	29.14	1.008±.054	0.920±.021	+0.088±.058
August 1...	30.0°	29.07	0.798±.039	0.580±.029	+0.218±.049
August 5...	21.0°	28.92	0.750±.052	0.375±.017	+0.375±.055
August 8...	35.0°	29.03	1.628±.161	0.920±.036	+0.708±.170
August 12..	23.5°	29.16	1.223±.018	0.665±.012	+0.558±.022
August 14..	28.0°	29.07	1.710±.043	0.790±.026	+0.920±.050
August 15..	31.0°	29.21	1.405±.012	0.525±.021	+0.880±.024
August 16..	32.0°	29.16	1.480±.033	0.505±.021	+0.975±.039
August 17..	29.5°	29.50	1.683±.049	0.478±.023	+1.205±.054
August 19..	26.5°	29.53	1.683±.042	0.400±.014	+1.283±.004
August 21..	33.0°	29.21	1.948±.016	0.430±.010	+1.518±.019
August 22..	33.0°	29.17	2.655±.055	0.588±.018	+2.067±.058
August 23..	33.0°	29.10	2.715±.074	0.633±.014	+2.082±.075
August 24..	34.0°	29.02	2.690±.060	0.695±.007	+1.995±.060
August 26..	30.5°	28.96	2.275±.064	0.468±.006	+1.807±.064

Memoir 29, *The Lecithin Content of Butter and Its Possible Relationship to the Fishy Flavor,* the third preceding number in this series of publications, was mailed on December 23, 1919.